

LIMIT ON OVERSHOOTING FROM THE CONVECTIVE CORE IN UPPER MAIN-SEQUENCE STARS

RICHARD B. STOTHERS AND CHAO-WEN CHIN
 NASA/Goddard Space Flight Center, Institute for Space Studies
 Received 1989 September 19; accepted 1989 October 6

ABSTRACT

Overshooting of convective elements far beyond the classical Schwarzschild convective core boundary in theoretical models of massive ZAMS stars is found to lead to significant reductions of stellar luminosity and radius, provided that the temperature gradient in the overshoot region can be approximated by the adiabatic gradient. Comparison of these theoretical models with binary star data for the mass range 5–15 M_{\odot} indicates that the ratio of overshoot distance to pressure scale height is probably less than 1.5. This result apparently excludes any overshooting theories that predict very extended adiabatic convective cores.

Subject headings: convection — stars: evolution — stars: interiors

I. INTRODUCTION

The size of the convective core in a star on the upper main sequence strongly influences the star's subsequent evolution. However, this critical structural quantity is still very poorly determined. The usual Schwarzschild condition (equality of the radiative and adiabatic temperature gradients) that has been standard to define the convective core boundary determines only where the buoyancy acceleration, not the velocity, of an upward-moving convective element vanishes. The distance of convective overshooting, d , beyond the classical core boundary is often expressed as a multiple of the local pressure scale height H_p . Some, but not all, current theories suggest that d/H_p is roughly constant during the main-sequence phase of evolution and that it is also only a weak function of stellar mass. Predicted values of d/H_p for unevolved stars are either very small, ~ 0 (Langer 1986), or relatively large, 1.3–2 (Xiong 1985, 1986), ~ 1.8 (Cloutman 1987), and ~ 2 (Doom 1985). However, Baker and Kuhfuss (1987) as well as Eggleton (1983) have pointed out several inconsistencies in Roxburgh's (1978) formalism, which was used in Doom's (1985) stellar models, while Renzini (1987) has discussed other inconsistencies affecting all of the older approaches that were based on mixing-length theory, including Langer's (1986) approach.

Since theory alone is an inadequate guide in this situation, various authors have attempted to infer d/H_p by comparing suitable stellar models with observed stars. The width of the upper main-sequence band in the H-R diagram is sensitive to d/H_p and has been used to infer values of ~ 0 (Vanbeveren 1987), 0.2–0.3 (Maeder and Mermilliod 1981; Mermilliod and Maeder 1986; Maeder and Meynet 1987, 1989; Grenier *et al.* 1985), 0.5–0.8 (Bressan, Bertelli, and Chiosi 1981; Bertelli, Bressan, and Chiosi 1984, 1985), ~ 0.7 (Stothers and Chin 1985), 0.3–1.7 (Doom 1982*a, b*), and ~ 2 (Doom 1985). In view of such discrepant results, more precise observational data are probably needed before a conclusive test can be made by using this approach. Stars in the lower main-sequence band have been similarly examined and some evidence found for substantial convective core overshooting (Barbaro and Pigatto 1984; Chiosi and Pigatto 1986; Mazzei and Pigatto 1988, 1989; Chiosi *et al.* 1989), but this conclusion has also been questioned (Brocato and Castellani 1988; Brocato *et al.* 1989). Masses of O and B stars in evolved main-sequence binary

systems seem to suggest a large amount of convective core overshooting, like that predicted by Doom (Hilditch and Bell 1987), but masses of Wolf-Rayet stars in evolved binary systems indicate very little overshooting (Schulte-Ladbeck 1989). Other observational tests have been devised and applied to stars in more advanced phases of evolution, but these tests suffer from proportionately greater uncertainties.

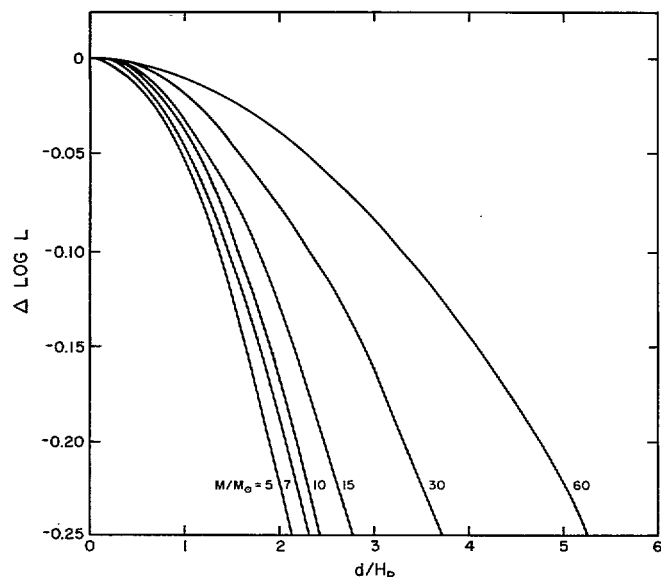
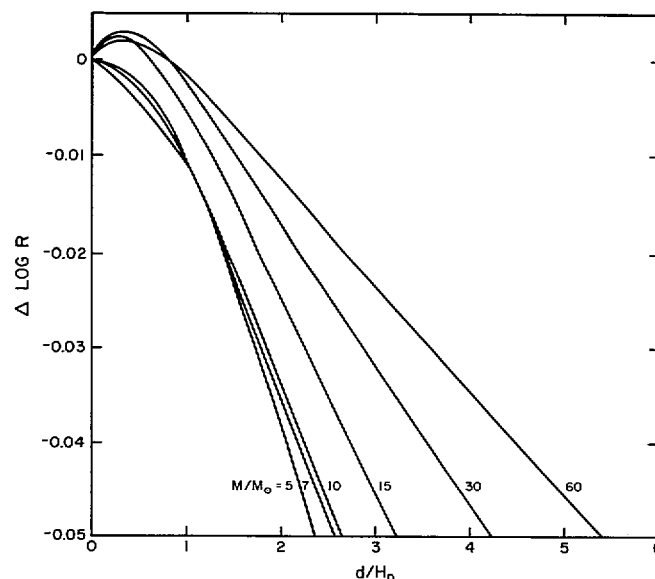
The safest stars to use are surely the simplest ones—the zero-age main-sequence (ZAMS) stars. We have found that it is possible to place a provisional upper limit on the extent of convective core overshooting in at least these unevolved (or slightly evolved) stars by comparing observed and predicted masses, luminosities, and radii. The tentative nature of our conclusion arises from the present uncertainty about the proper temperature gradient to use in the overshoot region.

II. INPUT DATA FOR THE MODELS

To calculate the new stellar models, standard input physics have been adopted, except that in the region of convective overshooting the temperature gradient has been taken to be the adiabatic one. Virtually all authors who have calculated evolution with imposed amounts of convective overshooting have used this assumption. Maeder (1975) and Doom (1985) have estimated that the adiabatic gradient is a good approximation throughout the overshoot region, as it also appears to be in at least a significant part of this region in Cloutman's (1987) models for a star of 15.57 M_{\odot} . In Xiong's (1985) models, however, the radiative gradient is found more nearly to apply. It is obvious that, by using ZAMS models, we will be able to test only this one aspect of the different overshooting theories.

Computationally, it is sufficient to specify in our models the mass fraction of the convective core boundary q_c and then, after each model has been calculated, to evaluate d/H_p between this boundary and the mass fraction q_s where the radiative and adiabatic temperature gradients are formally equal. Sequences of stellar models with increasing q_c have been computed for masses of 5, 7, 10, 15, 30, and 60 M_{\odot} .

Chemical composition in our models is taken to be the same as that derived from spectroscopic observations of young stars and H II regions. Accordingly, the helium abundance Y lies between 0.23 and 0.30 (Boesgaard and Steigman 1985; Brown 1986; Peimbert 1986), while the metal abundance Z lies

FIG. 1.—Change of luminosity with overshoot parameter d/H_p FIG. 2.—Change of radius with overshoot parameter d/H_p

between 0.02 and 0.04 (Nissen 1980; Bell and Dreiling 1981). Some evidence suggests that Y and Z are positively correlated (e.g., Peimbert 1986). We therefore adopt $(Y, Z) = (0.24, 0.02)$ for our “standard” composition, but also consider $(Y, Z) = (0.30, 0.04)$ in another set of stellar models. These two compositions will suffice, because the stellar luminosity is affected primarily by changes in Y and the stellar radius primarily by changes in Z .

III. PROPERTIES OF THE MODELS

Increasing the mass of the convective core is found to reduce the star’s luminosity (Fig. 1). Although this result was already known in the case of small values of d/H_p (Maeder 1975), the large range of the luminosity drop for greater overshoot distances seems to have escaped attention. Radius also declines, except in cases where d/H_p is less than 0.8 for stellar masses above $10 M_\odot$ (Fig. 2). Effective temperature, however, monotonically declines at all masses. With the same value of d/H_p , all of these drops of photospheric quantities are much diminished in the more massive stars because these stars already possess convective cores that contain a large fraction of the total mass.

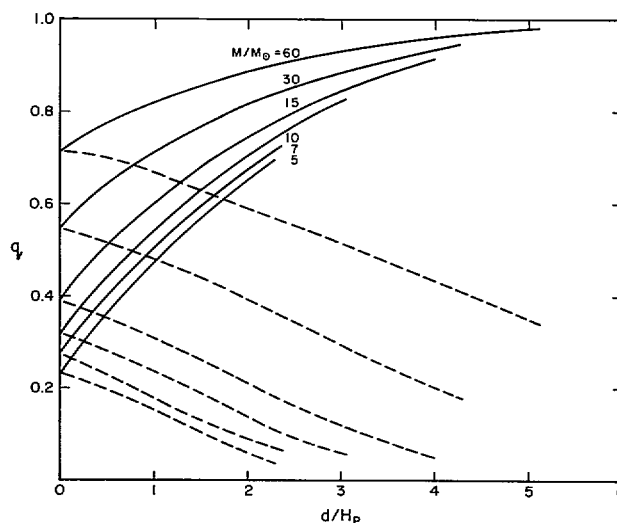
Since a drop in luminosity reduces the radiative temperature gradient, the mass of the Schwarzschild convective core shrinks (Fig. 3). In the case where q_s vanishes (or actually a little before this situation arises), it is pointless to calculate convective overshooting because there no longer exists any seed convective region from which the moving elements could arise. This situation is reached at smaller values of d/H_p in the less massive stars (Fig. 3). In models of $5 M_\odot$ without overshooting, the radius of the Schwarzschild convective core is only 0.8 of a pressure scale height; therefore, a fair test of the possibility of large adiabatic cores in ZAMS stars must realistically be based on stars that are not significantly less massive than $\sim 5 M_\odot$.

At first sight, it may seem paradoxical that, although the ZAMS luminosity and radius are lowered by overshooting, evolutionary changes eventually brighten and expand the star beyond what is achieved in the absence of overshooting (Stothers and Chin 1985). The reason, however, is that convec-

tive overshooting produces a larger mixed region in which hydrogen is eventually depleted and the mean molecular weight of the star is increased. In contrast, the temperature gradient exerts a higher order effect, which is significant only in the ZAMS models.

IV. COMPARISON OF MODELS WITH OBSERVATIONS

Hilditch and Bell (1987) have compiled the most accurate observational data available on massive O and B components of detached close binary systems. Their tabulation is an update of Popper’s (1980) critical compilation. The (mass, luminosity) diagram for their stars, including estimated error bars, is shown in Figure 4. A lower envelope to the plotted points represents unevolved stars and agrees closely with the theoretical line predicted for such stars with *no* convective core overshooting. This coincidence has been known for a long time,

FIG. 3.—Change of two critical core mass fractions with overshoot parameter d/H_p : q_c , convective core boundary (solid lines); q_s , classical Schwarzschild core boundary (dashed lines).

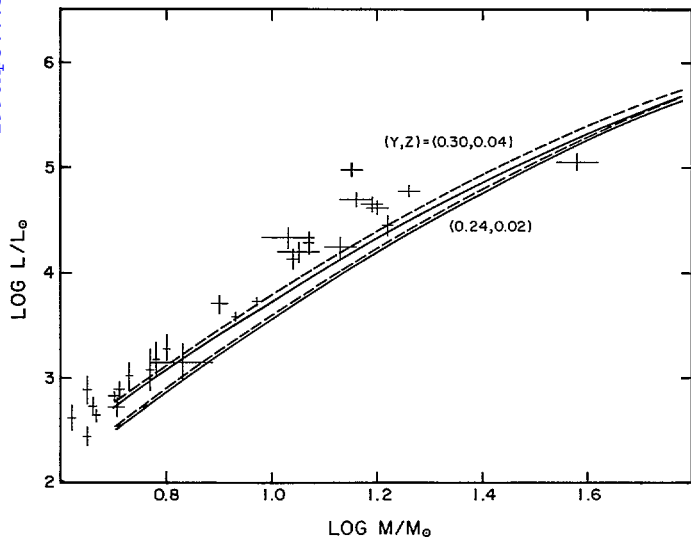


FIG. 4.—Mass vs. luminosity, for observed members of detached close binary systems. Curved lines are the loci of theoretical ZAMS models for two different chemical compositions: $(Y, Z) = (0.24, 0.02)$ (solid lines) and $(0.30, 0.04)$ (dashed lines). Upper and lower lines of each type refer to $d/H_p = 0$ and $d/H_p = 2$, respectively.

and therefore has served as an alternative way of estimating the helium abundances of unevolved stars (Popper *et al.* 1970; Stothers 1973; Lacy 1979). However, the allowable range of the spectroscopically derived helium abundances is now so small that it actually has rather little influence on the theoretical mass-luminosity relation. Reductions of the stars' luminosities by axial rotation, which is observed to be relatively slow and is also probably roughly uniform in the massive ZAMS components of detached close binary systems, should also be rather slight (Faulkner, Roxburgh, and Strittmatter 1968; Sackmann 1970; Stothers 1980). From Figure 4, it is clear that a value of d/H_p as large as ~ 2 can be ruled out. Comparing Figure 1, we believe that d/H_p is probably even less than 1.5.

In the (mass, radius) diagram, the situation is less clear, because radius is more sensitive to the uncertain metals abun-

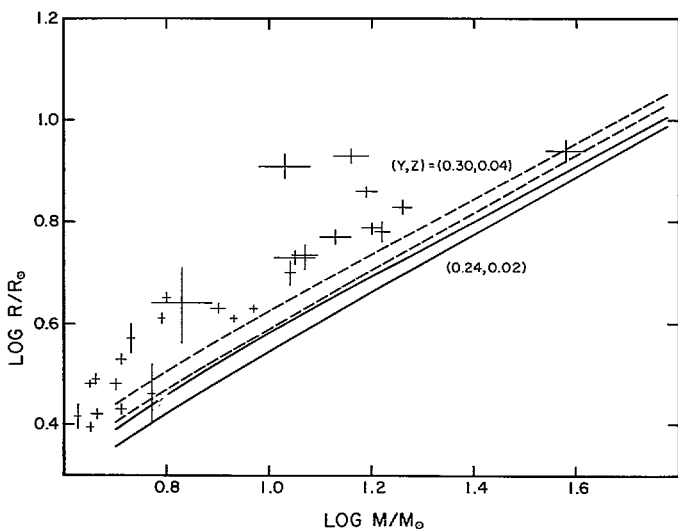


FIG. 5.—Mass vs. radius, for observed members of detached close binary systems. Same notation as for Fig. 4.

dance and therefore to any important remaining uncertainties in the calculation of the metals opacities. All that one may legitimately conclude from Figure 5 is that Z is significantly closer to 0.04 than to 0.02, if the present opacities are essentially correct (see also Popper *et al.* 1970; Lacy 1979; Popper 1982), and that d/H_p is, formally, likely to be less than ~ 2 .

The (luminosity, effective temperature) diagram gives essentially no information about d/H_p , because the stars' positions merely shift down the ZAMS line as d/H_p is increased (Fig. 6). However, the chemical composition can be estimated from a straight comparison of the stellar models with Blaauw's (1963) empirical ZAMS, which has been transformed to bolometric quantities by model-atmosphere relations derived by Morton and Adams (1968). Blaauw's ZAMS for B stars is assumed to be basically correct as it stands (see the discussion in Stothers 1983), while Morton and Adams' transformations lie near the middle of the more recently proposed transformations from observational to bolometric quantities. Figure 6 indicates that (Y, Z) is apparently closer to $(0.30, 0.04)$ than to $(0.24, 0.02)$. Since Figure 5 indicates the same result, our theoretical interpretation of the (mass, radius) diagram in terms of $d/H_p < 2$ is strengthened.

V. CONCLUSION

Theoretical models of massive ZAMS stars that include overshooting from the convective core show observable reductions of luminosity and radius if the overshoot parameter d/H_p is large enough and if the temperature gradient in the overshoot region is close to the adiabatic gradient. Comparison of these models with binary star data for the mass range $5\text{--}15 M_\odot$ implies that d/H_p is probably less than 1.5. A more accurate interpretation, however, is that the nearly adiabatic layers of the overshoot region are inferred to extend upward a distance less than $1.5H_p$, since the upper layers of this region could be essentially radiative (Baker and Kuhfuss 1987). Owing to the fact that evolution on the upper main sequence probably leads to a monotonic shrinkage of the convective

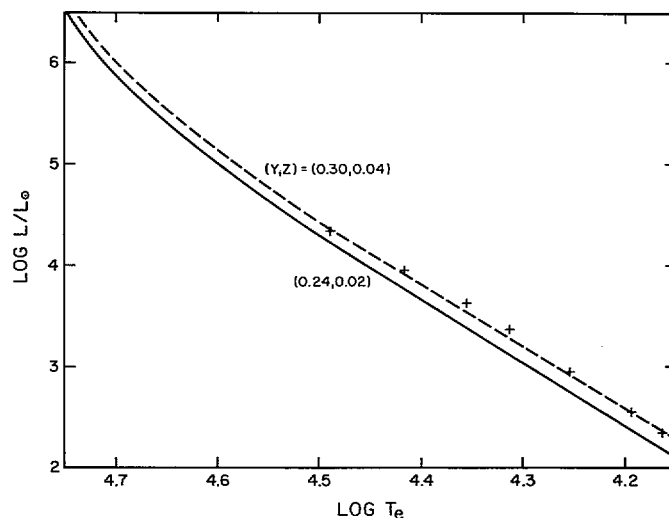


FIG. 6.—H-R diagram for theoretical ZAMS models with two different chemical compositions. In each case, models with overshoot parameters $d/H_p \leq 2$ lie essentially along the same locus. The observed ZAMS is indicated by a series of plus signs.

core, upward-moving convective elements would continue to penetrate into a chemically homogeneous region, and so the upper limit derived here for d/H_p would be expected to apply also to the later main-sequence stages. Although the theoretic

cal models are not sensitive enough (and the observational data are not abundant enough) to determine a useful upper limit on d/H_p for ZAMS stars more massive than $\sim 15 M_\odot$, we conjecture that the same upper limit applies.

REFERENCES

- Baker, N. H., and Kuhfuss, R. 1987, *Astr. Ap.*, **185**, 117.
 Barbaro, G., and Pigatto, L. 1984, *Astr. Ap.*, **136**, 355.
 Bell, R. A., and Dreiling, L. A. 1981, *Ap. J.*, **248**, 1031.
 Bertelli, G., Bressan, A. G., and Chiosi, C. 1984, *Astr. Ap.*, **130**, 279.
 ———. 1985, *Astr. Ap.*, **150**, 33.
 Blaauw, A. 1963, in *Stars and Stellar Systems*, Vol. 3, *Basic Astronomical Data*, ed. K. A. Strand (Chicago: University of Chicago Press), p. 383.
 Boesgaard, A. M., and Steigman, G. 1985, *Ann. Rev. Astr. Ap.*, **23**, 319.
 Bressan, A. G., Bertelli, G., and Chiosi, C. 1981, *Astr. Ap.*, **102**, 25.
 Brocato, E., Buonanno, R., Castellani, V., and Walker, A. R. 1989, *Ap. J. Suppl.*, **71**, 25.
 Brocato, E., and Castellani, V. 1988, *Astr. Ap.*, **203**, 293.
 Brown, P. J. F. 1986, *Irish A.J.*, **17**, 477.
 Chiosi, C., Bertelli, G., Meylan, G., and Ortolani, S. 1989, *Astr. Ap.*, **219**, 167.
 Chiosi, C., and Pigatto, L. 1986, *Ap. J.*, **308**, 1.
 Cloutman, L. D. 1987, *Ap. J.*, **313**, 699.
 Doom, C. 1982a, *Astr. Ap.*, **116**, 303.
 ———. 1982b, *Astr. Ap.*, **116**, 308.
 ———. 1985, *Astr. Ap.*, **142**, 143.
 Eggleton, P. P. 1983, *M.N.R.A.S.*, **204**, 449.
 Faulkner, J., Roxburgh, I. W., and Strittmatter, P. A. 1968, *Ap. J.*, **151**, 203.
 Grenier, S., Gómez, A. E., Jaschek, C., Jaschek, M., and Heck, A. 1985, *Astr. Ap.*, **145**, 331.
 Hilditch, R. W., and Bell, S. A. 1987, *M.N.R.A.S.*, **229**, 529.
 Lacy, C. H. 1979, *Ap. J.*, **228**, 817.
 Langer, N. 1986, *Astr. Ap.*, **164**, 45.
 Maeder, A. 1975, *Astr. Ap.*, **40**, 303.
 Maeder, A., and Mermilliod, J.-C. 1981, *Astr. Ap.*, **93**, 136.
 Maeder, A., and Meynet, G. 1987, *Astr. Ap.*, **182**, 243.
 ———. 1989, *Astr. Ap.*, **210**, 155.
 Mazzei, P., and Pigatto, L. 1988, *Astr. Ap.*, **193**, 148.
 ———. 1989, *Astr. Ap.*, **213**, L1.
 Mermilliod, J.-C., and Maeder, A. 1986, *Astr. Ap.*, **158**, 45.
 Morton, D. C., and Adams, T. F. 1968, *Ap. J.*, **151**, 611.
 Nissen, P. E. 1980, in *IAU Symposium 85, Star Clusters*, ed. J. E. Hesser (Dordrecht: Reidel), p. 51.
 Peimbert, M. 1986, *Pub. A.S.P.*, **98**, 1057.
 Popper, D. M. 1980, *Ann. Rev. Astr. Ap.*, **18**, 115.
 ———. 1982, *Ap. J.*, **254**, 203.
 Popper, D. M., Jorgensen, H. E., Morton, D. C., and Leckrone, D. S. 1970, *Ap. J. (Letters)*, **161**, L57.
 Renzini, A. 1987, *Astr. Ap.*, **188**, 49.
 Roxburgh, I. W. 1978, *Astr. Ap.*, **65**, 281.
 Sackmann, I.-J. 1970, *Astr. Ap.*, **8**, 76.
 Schulte-Ladbeck, R. E. 1989, *A.J.*, **97**, 1471.
 Stothers, R. B. 1973, *Ap. J.*, **184**, 181.
 ———. 1980, *Ap. J.*, **242**, 756.
 ———. 1983, *Ap. J.*, **274**, 20.
 Stothers, R. B., and Chin, C.-w. 1985, *Ap. J.*, **292**, 222.
 Vanbeveren, D. 1987, *Astr. Ap.*, **182**, 207.
 Xiong, D. R. 1985, *Astr. Ap.*, **150**, 133.
 ———. 1986, *Astr. Ap.*, **167**, 239.

CHAO-WEN CHIN and RICHARD B. STOTHERS: Institute for Space Studies, NASA/Goddard Space Flight Center, 2880 Broadway, New York, NY 10025